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Spatial scales of pollution from variable resolution satellite imaging

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ABSTRACT

The Moderate Resolution Imaging Spectroradiometer (MODIS) provides daily global coverage, but the 10 km resolution of its aerosol optical depth (AOD) product is not adequate for studying spatial variability of aerosols in urban areas. Recently, a new Multi-Angle Implementation of Atmospheric Correction (MAIAC) algorithm was developed for MODIS which provides AOD at 1 km resolution. Using MAIAC data, the relationship between MAIAC AOD and $PM_{2.5}$ as measured by the EPA ground monitoring stations was investigated at varying spatial scales. Our analysis suggested that the correlation between $PM_{2.5}$ and AOD decreased significantly as AOD resolution was degraded. This is so despite the intrinsic mismatch between $PM_{2.5}$ ground level measurements and AOD vertically integrated measurements. Furthermore, the fine resolution results indicated spatial variability in particle concentration at a sub-10 km scale. Finally, this spatial variability of AOD within the urban domain was shown to depend on $PM_{2.5}$ levels and wind speed.

1. Introduction

Characterizing the spatial variability of aerosol concentration is essential for human exposure estimates and for interpretation of epidemiological studies (Zhu et al., 2006; Bell et al., 2010). Because existing $PM_{2.5}$ ground-monitoring networks encompass a relatively small number of stations per urban area, the information they provide is not sufficient to adequately characterize spatial variability of particles within a large metropolitan area. On other hand, satellite-based aerosol optical depth (AOD) retrievals, which are measures of extinction of electromagnetic radiation due to the presence of aerosols in an atmospheric column, may provide some indication of the extent of spatial heterogeneity of particle concentrations. However, the horizontal spatial resolution of most AOD retrievals varies between 4 km (Geostationary Operational Environmental Satellite: GOES) and 17.6-km (Multi-angle Imaging SpectroRadiometer: MISR) which is too coarse to characterize spatial variability within urban areas. Several studies have used high spatial resolution satellites like LANDSAT (30 m) (e.g. Lyapustin et al., 2004; Hadjimitsis and Clayton, 2009) and SPOT (15 m) (e.g. Liu et al., 1996; Liu and Liu, 2009) to derive AOD for certain days and events; however, the long revisit time of these systems renders them impractical.

The Moderate Resolution Imaging Spectroradiometer (MODIS) provides daily near-global distributions of aerosol optical depth (AOD) at a resolution of 10 km. The widely anticipated 3 km MODIS AOD product is expected to be generated as part of the Collection 6 re-processing. On the other hand, a recently developed Multi-Angle Implementation of Atmospheric Correction (MAIAC) algorithm (Lyapustin et al., 2011b) provides a 1 km resolution aerosol product which makes it an attractive alternative for urban studies. Would this improved AOD spatial resolution yield a better proxy for the $PM_{2.5}$ measured at the ground?

The answer to this question is not obvious. Indeed, while the satellite-derived AOD integrates the entire vertical column, $PM_{2.5}$ data is obtained near the surface, so that the two parameters need not be tightly correlated regardless of the resolution. Furthermore, because the main variability for a regional (or larger) scale analysis may be driven by meteorological conditions, long range transport, or the impact of distant regional sources, we cannot presume that the relationship between the two parameters will improve just by having higher AOD resolution. In addition, even though both high and low resolution AOD data will capture the pattern of pollution transport, the variable presence of particles in the column above

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ground level will most likely reduce the correlation of AOD with $PM_{2.5}$. Despite these potential confounding factors high resolution AOD may still provide useful information about local conditions and intra-urban variability at scales below 10 km.

There are several factors which limit AOD-$PM_{2.5}$ correlation: the impact of the aerosol vertical profile that is responsible for the difference between the column (AOD) and the near-surface ($PM_{2.5}$) measurements; the complex role of relative humidity; wind speed; particle size distribution; as well as particle composition, etc. (Wang and Christopher, 2003). Hoff and Christopher (2009) gave a detailed overview of this problem, based on the review of over 30 papers that investigated the correlation between total-column AOD and surface $PM_{2.5}$ measurements and these variables. These studies from across the globe reported a wide range of correlations between AOD and $PM_{2.5}$ mass. It is therefore somewhat surprising that our results show a robust improvement in the association between $PM_{2.5}$ and AOD with increased AOD spatial resolution.

In this paper we use 1 km resolution AOD data retrieved for the Boston metropolitan area to determine whether the relation between $PM_{2.5}$ concentrations measured at the ground and AOD values becomes stronger as the spatial resolution of the AOD retrieval increases. Furthermore, we investigate the extent of spatial variability of AOD in relation to both $PM_{2.5}$ particle levels and wind speed.

2. Material and methods

2.1. Ground-level $PM_{2.5}$ data

Twenty-four hour integrated $PM_{2.5}$ concentrations were measured at 26 U.S. Environmental Protection Agency (EPA) $PM_{2.5}$ monitoring sites during the year 2003 (Fig. 1 and Table 1). These include 15 sites from Massachusetts (MA) and 11 sites from Connecticut (CT). Sampling frequency differed by site and included samples collected every day, every third day, and every sixth day. Additionally, we used 24 h integrated $PM_{2.5}$ concentrations from the Harvard School of Public Health (HSPH) supersite located near downtown Boston. Data from this site have been used in a large number of epidemiological studies to assess the temporal variability of individual and population exposures in the region.

2.2. Satellite data

A new algorithm MAIAC (Lyapustin et al., 2011a,b) has been developed to process MODIS data. MAIAC retrieves aerosol parameters over land at 1 km resolution simultaneously with parameters of a surface bidirectional reflectance distribution function (BRDF). This is accomplished by using the time series of MODIS measurements and simultaneous processing of a group of pixels. The MAIAC algorithm ensures that the number of measurements exceeds the number of unknowns, a necessary condition for solving an inverse problem that does not require the assumptions typically used by current operational algorithms. The MODIS time series accumulation also provides multi-angle coverage for every surface grid cell, which is required for the BRDF retrievals from MODIS data. The aerosol parameters include optical depth (total aerosol) and fine mode fraction. Following the MODIS operational aerosol algorithm (MOD04) (Levy et al., 2006, 2007), models for the fine and coarse aerosol fractions are specified regionally based on the climatology of the AErosol RObotic NETwork (AERONET) (Holben et al., 1998) sun-photometer data. AERONET validation over the continental USA showed that the MAIAC and MOD04 algorithms have a similar accuracy over dark and vegetated surfaces, but also showed that MAIAC generally improves accuracy over brighter surfaces, including most urban areas (Lyapustin et al., 2011b). The improved accuracy of MAIAC results from the explicit surface characterization method, in contrast to the empirical surface parameterization approach, utilized in the MOD04 algorithm. Further, MAIAC incorporates a cloud mask (CM) algorithm based on spatio-temporal analysis which augments traditional pixel-level cloud detection techniques (Lyapustin et al., 2008). In addition, the residual contamination by clouds and cloud shadows was reduced by discarding 2 pixels adjacent to detected clouds.

2.3. Data processing and analyses

$PM_{2.5}$ daily measurements and AOD retrievals for the year 2003 were used for our study. First, we study the link between AOD and $PM_{2.5}$ measurements at regional (New England area, ~600 km) and intra-urban (Boston, 10 km) scales. Since the sampling frequency of EPA stations included samples collected every day, every third day, and every sixth day, the number of available AOD-$PM_{2.5}$ pairs also varies by date and location. For regional AOD-$PM_{2.5}$ correlation, there were 70 days with at least two available pairs on a given day, including a total of 640 pairs. The days were selected according to snow-free and less than 20% cloud fraction conditions to mitigate the impact of errors from undetected clouds and snow. For the intra-urban AOD-$PM_{2.5}$ study we analyzed 10×10 km^2 area inside of Boston containing four EPA ground monitors and the Harvard Supersite. To take into account the variability of the sampling frequency of the EPA stations, only days with at least three available AOD-$PM_{2.5}$ pairs inside of a 10×10 km^2 box were selected (Table 1, stations s1–s5). There were a total of 107 pairs for 30 days with 3–5 observations.

Next, we explored the effect of AOD spatial resolution on the observed correlation between AOD and $PM_{2.5}$ for the New England region based on data for 70 selected days. These analyses were repeated for progressively degraded resolutions at 3, 5 and 10 km, obtained from the original 1 km AOD data by simple averaging. In addition, fine scale AOD variability, as evidenced by the coefficient of variation (CV, ratio of standard deviation to the mean) as a function of resolution (3, 5 and 10 km) was explored.

Finally, we investigated spatial variability of AOD in relation to both $PM_{2.5}$ particle levels and wind speed within the Boston metropolitan domain covering an area of 60×70 km (highlighted by rectangle in Fig. 1). The total of 64 snow-free and low cloudiness (<20%) days were available for this study. In addition, variability (CV) of both AOD and $PM_{2.5}$ concentrations were also assessed in Boston, at a scale of 10×10 km^2.

3. Results and discussion

3.1. Analysis of regional and intra-urban AOD-PM correlation

Fig. 2 shows the high resolution MAIAC 1 km (left column) and low resolution MOD04 10 km (right column) AOD retrievals, representing low pollution (based on the Air Quality Index [AQI] designation for $PM_{2.5}$ concentrations less than 15 μg m^{-3}, Fig. 2A), and moderate to USG (unhealthy for specific groups such as elderly and children) pollution (moderate: 15–40 μg m^{-3}, USG: 40–65 μg m^{-3}, Fig. 2B) days. The high resolution data reveal a substantial spatial variability of AOD both at moderate and low levels of pollution which cannot be captured using a coarse 10 km scale.

The left panel (a) of Fig. 3 shows the relationship between MODIS 1 km AOD and the corresponding 24-h integrated $PM_{2.5}$ concentrations measured at the 27 EPA sites in New England. The coefficient of determination ($R^2 = 0.47$) suggests that AOD is a reasonably good proxy for $PM_{2.5}$ ground concentrations. For the east coast, the reported correlation coefficient (R) based on 10 km MOD04 product ranged from 0.65 to 0.76 ($R^2 = 0.42$–0.57) (Hoff and Christopher, 2009). Our analysis shows that the 1 km MAIAC AOD values provide a similar level of correlation at a regional scale.

The high resolution AOD potentially carries information about local-scale variability, which is especially important for highly populated urban areas. Since each $PM_{2.5}$ value for a given station in Fig. 3 represents a daily averaged value, we define the local variability as the variability in daily averaged $PM_{2.5}$ values among different EPA stations (from 3 to 5) in the 10×10 km^2 box. The bottom plot (b) on the left panel of Fig. 3 shows an intra-urban AOD-$PM_{2.5}$ correlation in Boston with $R^2 = 0.62$ for year 2003. It is not entirely unexpected that the local variability of $PM_{2.5}$ is captured better and with higher correlation with AOD than the regional variability. The intra-urban AOD-$PM_{2.5}$ correlation (Fig. 3b) includes the temporal meteorological variability for year 2003. At the regional scale, there is an additional spatial component of variability over the area of ~600 km which is expected to generally reduce the overall AOD-$PM_{2.5}$ correlation (Fig. 3a). Factors that affect AOD-$PM_{2.5}$ correlation include variations in aerosol type, its vertical profile, effects of atmospheric humidity, boundary layer height etc., which are more homogeneous at the local scale as compared to the regional scale. The best correlation can be observed at the local scale for daily data when the variability of the meteorological factors is the lowest. Several examples of daily AOD-PM correlations are shown on the right panel of Fig. 3c.

Finally, Fig. 3d presents the $PM_{2.5}$ distribution histograms at local and regional scales for 2003. As can be seen, the two

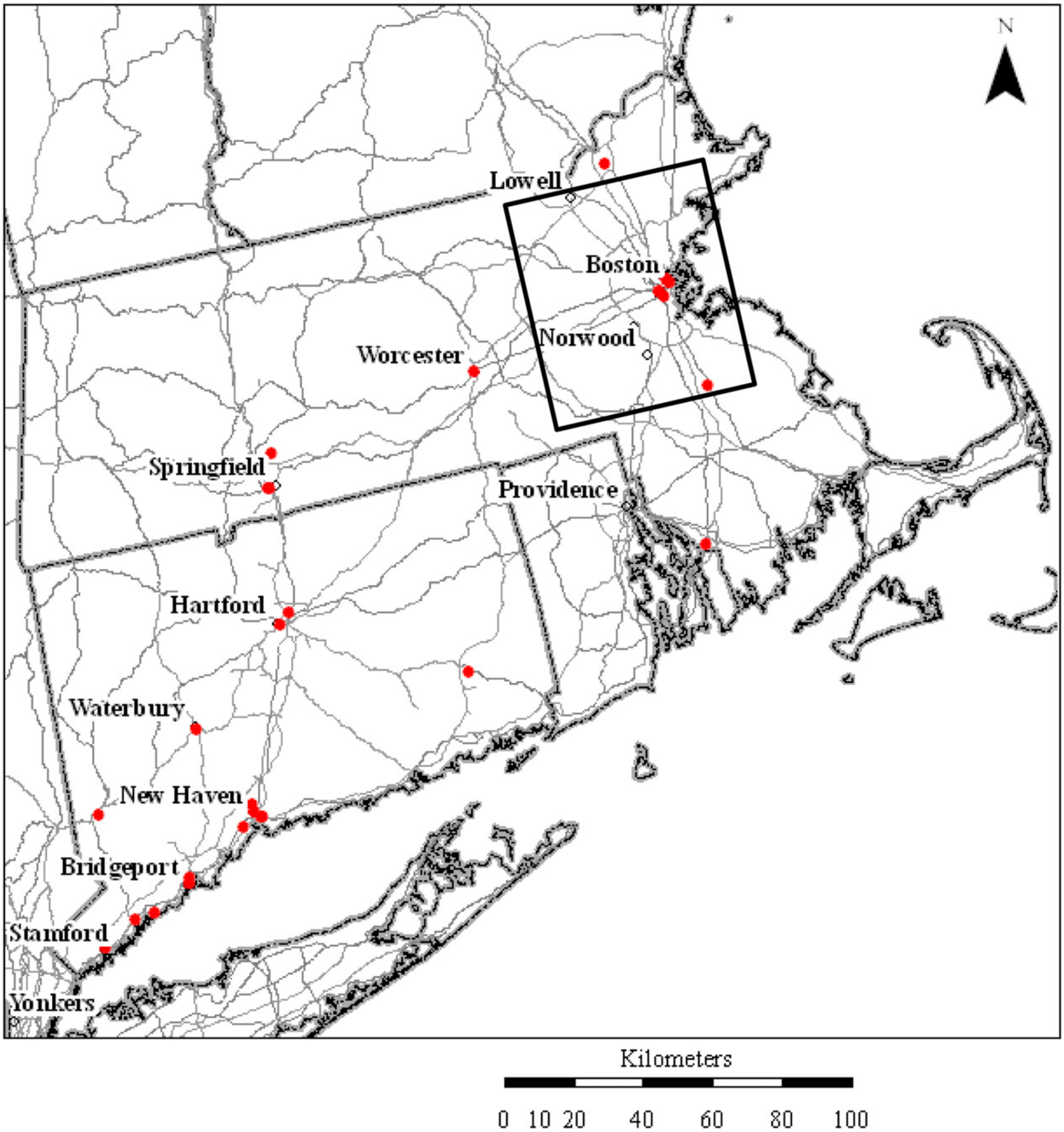

Fig. 1. Study area. The dots mark locations of the EPA $PM_{2.5}$ ground monitoring sites. The area highlighted by rectangle shows the 60 × 70 km^2 Boston metropolitan area.

distributions are generally similar with a rather high total range of variation. Based on this result, it seems unlikely that the observed improvement in AOD-$PM_{2.5}$ correlation could be caused by reduced and more homogeneous emissions in the Boston 10 km area as compared to that in the New England region.

3.2. *Effect of AOD spatial resolution*

As discussed in the previous section, a simple decrease of meteorological variability with decrease in the size of examined area may lead to an improvement of the AOD-PM correlation. This section examines the effect of spatial resolution of AOD product on AOD-PM correlation.

For this study, we assume that the coarser resolution can be adequately represented by a simple aggregation of the fine resolution AOD data. An illustration of this effect is given in Fig. 4, where the left panel shows a map of MAIAC AOD data for September 24, 2003, as well as the locations of five ground PM-monitoring stations used for the intra-urban analysis (highlighted by circles). The upper right plot shows a strong correlation between 1 km AOD and $PM_{2.5}$ on a low polluted day, with measured ground concentrations between 9.4 and 13.6 μg m^{-3}. Importantly, in this case the imaging resolution of AOD matches or surpasses resolution of the network of ground monitoring stations. As an extreme example, the lower right panel shows AOD at 10 km resolution, which no longer captures the one-to-one correspondence between $PM_{2.5}$ and AOD, since a single AOD value corresponds to the five different $PM_{2.5}$ values. *Hence, coarsening of AOD spatial resolution yields a spurious scatter.*

Next, we examined a more extensive data set to determine the correlation between collocated $PM_{2.5}$ and AOD pairs within Boston

Table 1
EPA ground monitoring sites used in this study over New England. In Italic Bold we highlight sites used to study intra-urban variability.

Site ID	City	Latitude	Longitude	
09-001-0010	Bridgeport, CT	41.17	−73.19	
09-001-0113	Bridgeport, CT	41.18	−73.19	
09-001-1123	Danbury, CT	41.40	−73.44	
09-001-2124	Stamford, CT	41.06	−73.53	
09-001-3005	Norwalk, CT	41.11	−73.41	
09-001-9003	Westport, CT	41.12	−73.34	
09-003-1003	E. Hartford, CT	41.78	−72.63	
09-003-1018	Hartford, CT	41.76	−72.67	
09-009-0018	New Haven, CT	41.29	−72.90	
09-009-0026	New Haven, CT	41.29	−72.89	
09-009-1123	New Haven, CT	41.31	−72.92	
09-009-2008	New Haven, CT	41.33	−72.92	
09-009-2123	Waterbury, CT	41.55	−73.04	
09-009-8003	W. Haven, CT	41.28	−72.96	
09-011-3002	Norwich, CT	41.52	−72.08	
25-005-1004	Fall River, MA	41.68	−71.17	
25-009-2006	Lynn, MA	42.47	−70.97	
25-009-5005	Haverhill, MA	42.77	−71.10	
25-013-0008	Chicopee, MA	42.19	−72.56	
25-013-0016	Springfield, MA	42.11	−72.59	
25-013-2009	Springfield, MA	42.11	−72.60	
25-023-0004	Brockton, MA	42.08	−71.01	
25-025-0027	***Boston, MA***	***42.37***	***−71.06***	S1
25-025-0042	***Boston, MA***	***42.33***	***−71.08***	S2
25-025-0043	***Boston, MA***	***42.36***	***−71.05***	S3
25-025-0002	***Boston, MA***	***42.35***	***−71.10***	S4
25-027-0020	Worcester, MA	42.27	−71.80	
Harvard supersite	***Boston, MA***	***42.34***	***−71.10***	S5

metropolitan area (60 × 70 km^2, Fig. 1, highlighted by rectangle). Fig. 5A shows distributions of the coefficients of determination corresponding to AOD spatial resolutions of 1, 3, 5 and 10 km. The degraded resolution was obtained by averaging the 1 km MAIAC AOD data. This figure shows that when MAIAC AOD data were averaged spatially to simulate coarser resolution of 3, 5 and 10 km and correlated with $PM_{2.5}$, the coefficient of determination between AOD and $PM_{2.5}$ weakened again markedly, from a maximum value of 0.46 at 1 km to a minimum value of 0.18. This trend confirms that the $PM_{2.5}$ variability at a sub-10 km scale is not captured by the coarser resolution AOD. Here we emphasize the particular importance of this finding for urban domains, governed by relatively more diverse pollution sources.

The examples presented in Figs. 4 and 5 clearly illustrate how step-wise increases in AOD spatial resolution correspond to increasing correlation with $PM_{2.5}$. The spurious scatter, present at a coarser resolution, renders the conversion less reliable, and may bias the slope/intercept statistics. This also implies that it is important to ensure that spatial resolution of the ground-monitoring network (distance to nearest neighbor) is matched or surpassed by the resolution of AOD data.

The aerosol spatial variability was next evaluated using the AOD coefficient of variation (CV) for the Boston metropolitan area (rectangle in Fig. 1) for each of the 64 selected days. Fig. 5B shows that the AOD variability decreases with coarsening resolution. Note that the conventional MOD04 10 km AOD retrieval may yield a lower CV than that of MAIAC for the same 10 km grid. For example, the MAIAC CVs for the urban domain for June 17 (clear

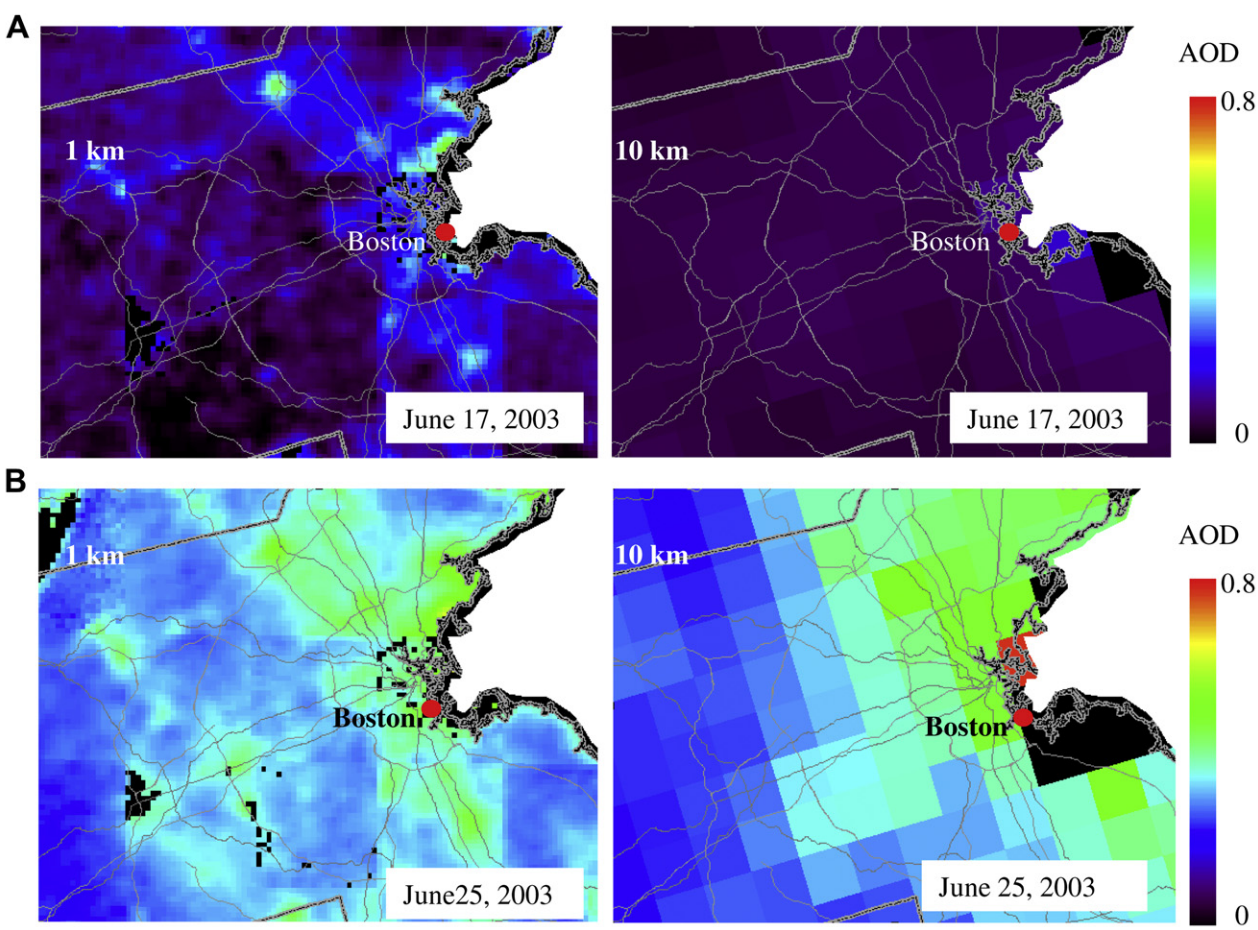

Fig. 2. MAIAC 1 km (left column) and MOD04 10 km (right column) AOD, representing low pollution (A) and moderate pollution (B) days as measured by $PM_{2.5}$. Note the loss of AOD variability on conventional images (right column). Consider left column only next. The 1 km AOD data display higher spatial variability regardless of the pollution level.

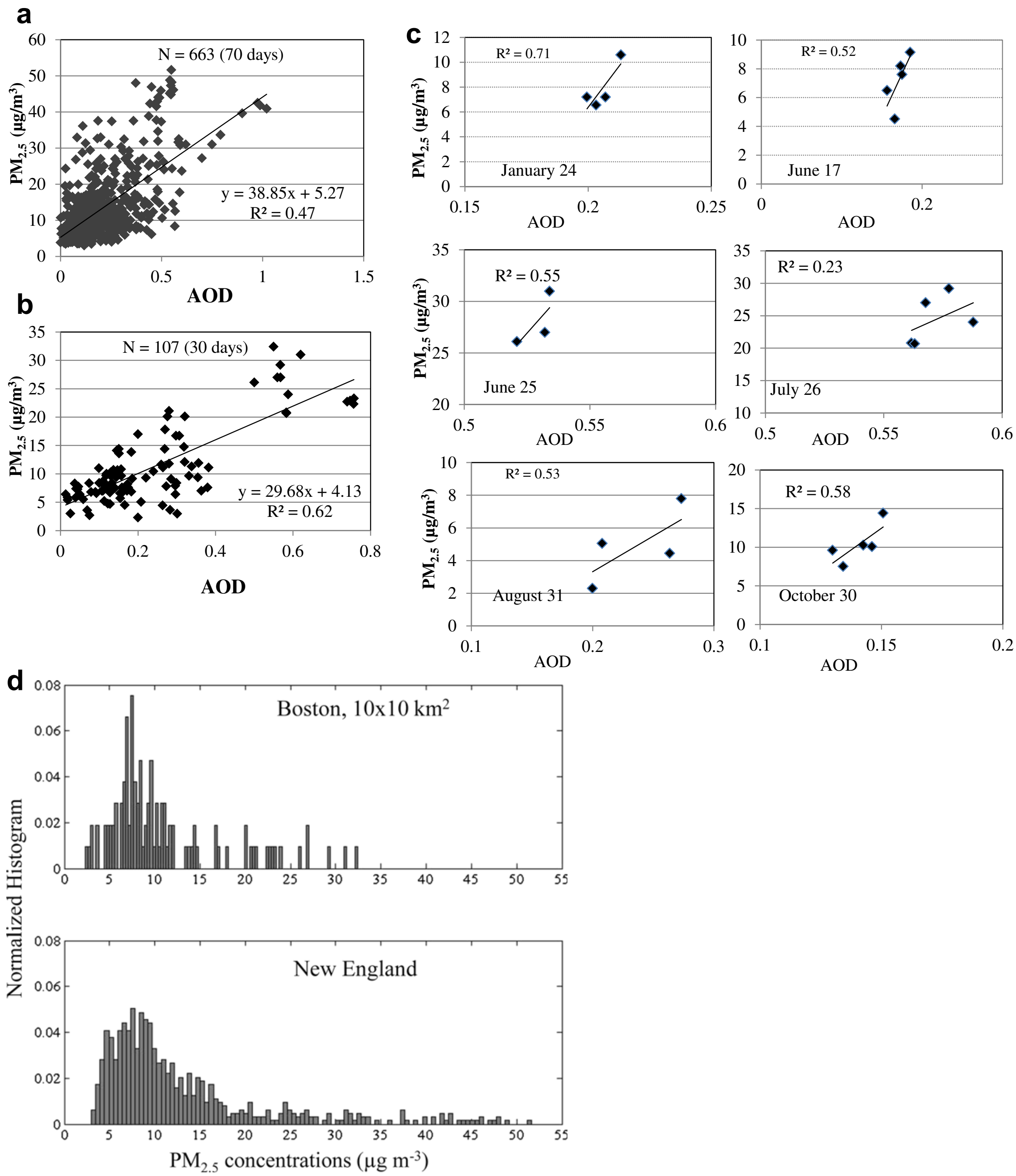

Fig. 3. Left panel: Regional (a) and Intra-urban (b) 1 km AOD-$PM_{2.5}$ correlation for 2003. Right panel (c): Examples of intra-urban daily correlation between 1 km AOD and $PM_{2.5}$ for six different days. Note up to 10 μg m^{-3} variability in $PM_{2.5}$ between EPA monitoring stations. (d): Normalized histogram of $PM_{2.5}$ concentrations for Boston (10 × 10 km^2 box, top) and New England (bottom) domains.

day) and June 25 (moderate pollution) (Fig. 2) are 0.36 and 0.42, respectively, while MOD04 10 km conventional retrieval gives lower CV AOD values of 0.17 and 0.20, respectively.

The upper panel of Fig. 6 presents AOD CV values calculated for the same domain (rectangle in Fig. 1) but conditioned on $PM_{2.5}$ concentrations. The distribution shown in the upper left panel corresponds to 35 low pollution days with $PM_{2.5} < 15$ μg m^{-3} (low pollution, AQI) whereas the upper right panel corresponds to 29 days with $PM_{2.5}$ concentration levels higher than 15 μg m^{-3} (moderate to USG pollution, AQI). The AOD CV for less polluted days exhibits higher AOD spatial variability, probably because the aerosols are not well mixed with the surrounding air. In contrast, during the medium to high pollution days, regional transport of pollution may obscure the effect of local sources, thereby decreasing the contrast in pollution levels within the domain. These results thus suggest that wind speed should also affect the range of variability.

With this in mind, we studied influence of wind speed on the AOD CV. The lower panel of Fig. 6 shows calculated AOD CVs conditioned on two ranges of wind speed measured at the Boston Logan airport: light and moderate-strong breeze days (based on the Beaufort scale). The lower left panel represents 16 days with a wind speed less than 3.5 m/s (light breeze), while the lower right panel represents 48 days with a wind speed ranging between 3.5 and 12 m/s (moderate-strong breeze). These results suggest a higher

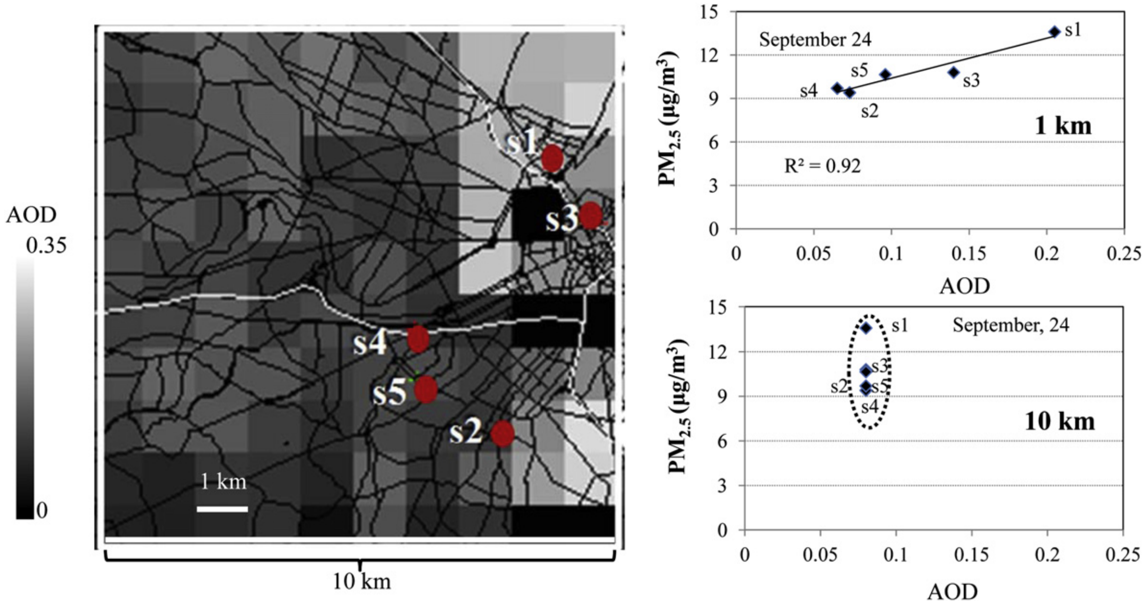

Fig. 4. Schematic explanation of worsening correlation as image resolution coarsens. Left: The 1 km MAIAC AOD image for September 24, 2003, with the rectangle covering the urban Boston area of 10 × 10 km^2 with five PM monitoring stations (circles). Right: The intra-urban AOD-$PM_{2.5}$ correlation at 1 km resolution (top), and illustration of a loss of spatial $PM_{2.5}$ information at 10 km resolution (lower) of AOD; Spurious scatter appears as the resolution coarsens, and one-to-one correspondence between $PM_{2.5}$ and AOD is lost.

variability in AOD values within the study domain during the lower wind speed conditions, which corresponds to weaker atmospheric mixing. In contrast, turbulent mixing by vigorous winds homogenizes the aerosol distribution, thereby reducing AOD spatial variability. This turbulent mixing perspective agrees with $PM_{2.5}$ data for urban areas, reported by Levy and Hanna (2011). They showed that aerosol concentration due to local sources tends to be inversely proportional to wind speed. They also observed that elevated concentrations at low wind speeds were indicative of enhanced contributions from local sources.

What variability in aerosols levels cannot be captured by currently available MOD04 retrieval? To answer this question, we calculated AOD CV and $PM_{2.5}$ CV at a scale of 10 × 10 km^2 (intra-urban domain) for both low and medium pollution days. Fig. 7 shows that low pollution days exhibit higher spatial variability of AOD and $PM_{2.5}$. For example, on a single low pollution day, the difference in $PM_{2.5}$ concentrations between different locations inside of 10 × 10 km^2 area can be as high as 7–8 μg m^{-3}. In contrast, as shown in Fig. 6 for a larger area, the medium pollution days generally exhibit lower spatial aerosol variability. Although these results may require confirmation with much larger statistical analysis, they suggest that the coarse spatial resolution may be adequate for the medium-high pollution days, while the low pollution days require higher resolution aerosol retrievals to characterize $PM_{2.5}$ spatial heterogeneity in urban environments.

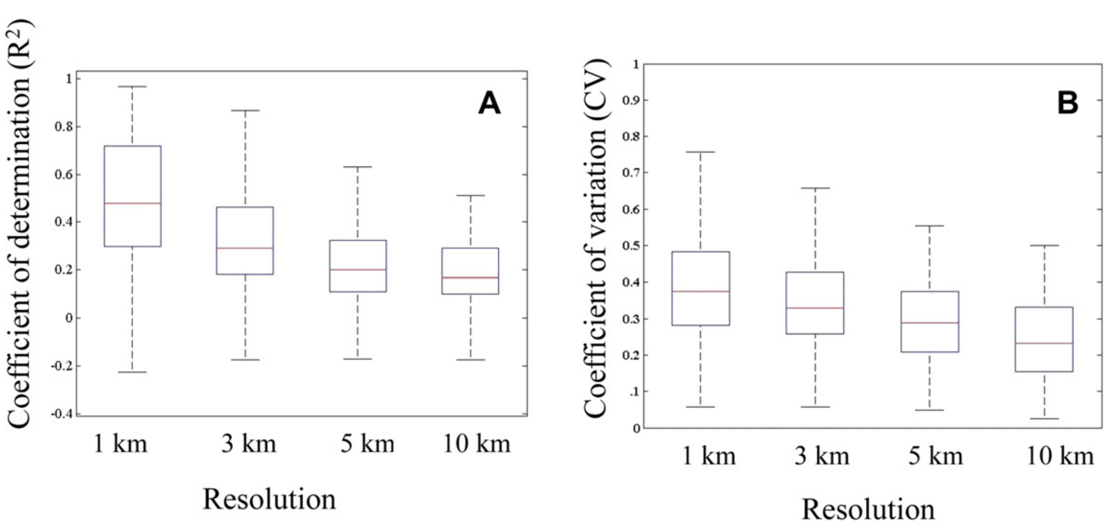

Fig. 5. A: Coefficient of determination (R^2) for $PM_{2.5}$, measured by the EPA ground-monitoring stations, and MAIAC retrieved AOD as a function of spatial resolution. The correlation deteriorates as imaging resolution coarsens towards the conventional 10 km. Red line represents the median value, the edges of the box are the 25th and 75th percentiles, the whiskers indicate the range. B: AOD coefficient of variation (stdev divided by the mean) also decreases with the coarsening resolution. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

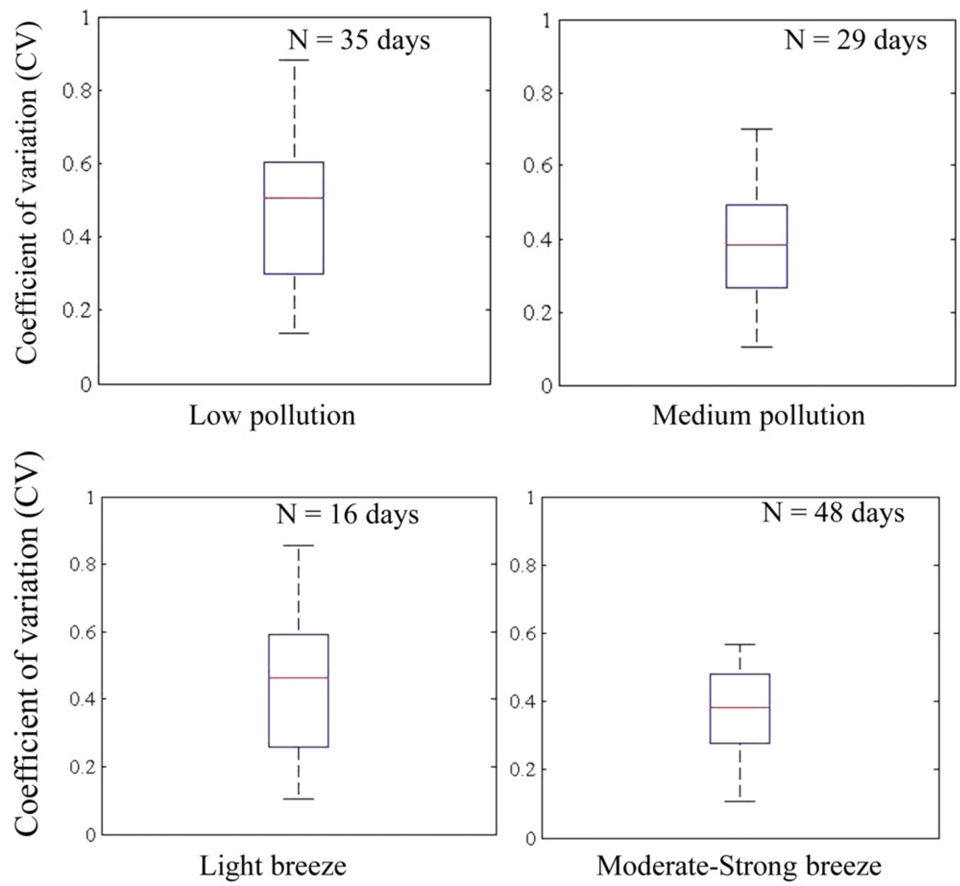

Fig. 6. Upper panels: AOD coefficient of variation (CV) calculated for the Boston metropolitan area but conditioned on $PM_{2.5}$ concentrations. Left panel shows low pollution days with $PM_{2.5}$ concentration less than 15 μg m^{-3}. Right panel shows CV for the moderate pollution days with $PM_{2.5} > 15$ μg m^{-3}. Lower panels: AOD CV conditioned on wind speed measured at the Logan airport. Left panel represents days with the measured wind speed <3.5 m/s (light breeze), whereas the right panel represents wind speed within 3.5–12 m/s range (moderate-strong breeze).

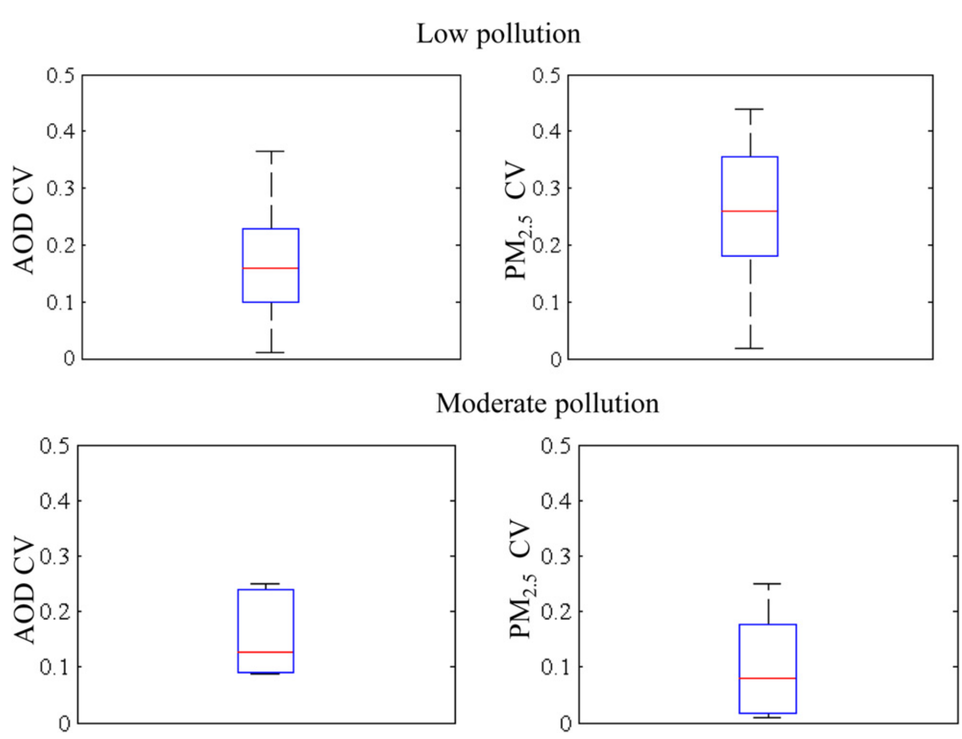

Fig. 7. AOD coefficient of variation (CV) and $PM_{2.5}$ CV calculated for the 10 × 10 km^2 area. Upper panel: low pollution days ($PM_{2.5} < 15$ μg m^{-3}); Lower panel: moderate pollution days ($PM_{2.5} > 15$ μg m^{-3}).

4. Concluding remarks

Until recently, the main source of global satellite aerosol data was the MODIS satellite MOD04 algorithm, which provides data at a 10 km resolution. In this paper we used the new high-resolution (1 km) AOD retrieval from MODIS data based on the MAIAC algorithm. Our analysis suggests that the correlation between $PM_{2.5}$ and AOD decreases significantly as AOD resolution is degraded. Furthermore, we have shown that the high spatial resolution is essential to improving $PM_{2.5}$ − AOD agreement. In addition, our results indicated a spatial variability in particle levels at a sub-10 km scale (e.g. intra-urban domain). Finally, we have shown that the AOD coefficient of variation (CV), which also decreases as resolution coarsens, is a useful measure of the AOD variability within urban domains. Although this decrease is perhaps to be expected, to the best of our knowledge this is the first time that a 1 km AOD data from MODIS has been used to demonstrate such trends.

Despite promising results, more data need to be processed and analyzed to understand the full potential and limitations of the high resolution MAIAC AOD product for improving the accuracy in $PM_{2.5}$ estimation. It is important to emphasize, though, that the information content of AOD data alone is limited, and the best results may be achieved by combining different data sources including, for example, the aerosol vertical profile information from satellite or ground-based lidars.

Competing interests

The authors declare they have no actual or potential competing financial interests.

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